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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

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TITLE: FRACTIONATION OF MACRO-MOLECULES USING  
ASYMMETRIC PULSED FIELD ELECTROPHORESIS

SPECIFICATION

BACKGROUND OF THE INVENTION

RELATED APPLICATIONS

This application claims the priority of Provisional Application Serial No. 60/256,298, filed December 18, 2000, the entire disclosure of which is expressly incorporated herein by reference.

GOVERNMENT RIGHTS

The present invention has been made under Federal Contract Grant No. MDA 972-00-1-0031 and the government may have certain rights to the subject invention.

FIELD OF THE INVENTION

The present invention relates to a method and apparatus for fractionating charged macro-molecules such as DNA using asymmetric pulsed field electrophoresis.

RELATED ART

The analysis and fractionation of large DNA molecules is a central step in large scale sequencing projects. Conventionally, gel electrophoresis is used to fractionate DNA molecules

according to their sizes. This method includes two steps: sample loading and fractionation. First, sample solution containing DNA is loaded into loading wells in the gel slab before the electric field is turned on. Then, an electric field is applied. The DNA molecules move in the opposite direction of the electric field because they are negatively charged. As the electric field is applied, DNA molecules travel at different speeds according to their sizes, but the directions in which they migrate are always the same. Eventually, sample DNA molecules are separated into different bands, each of which contains DNA molecules of the same size, as shown in **FIG. 1**. Shorter DNA fragments move faster than longer ones. Therefore, they are separated according to their sizes. However, this standard method only works effectively for DNA molecules smaller than 40 kbp. Above this range, the standard method has to be modified. In particular, the applied electric field can no longer be DC, but is made to alternate between two different orientations. This modified scheme (pulsed-field gel electrophoresis) is routinely used in modern molecular biology laboratories, but it typically takes a few days to fractionate one set of DNA samples.

What is needed, and has not heretofore been provided, is a method and apparatus for quickly, or even continuously, fractionating charged macro-molecules.

## OBJECTS AND SUMMARY OF THE INVENTION

It is an object of the present invention to provide a method and apparatus for quickly fractionating charged macro-molecules.

It is an additional object of the present invention to provide a method and apparatus for continuously fractionating charged macro-molecules.

It is a further object of the present invention to provide a method and apparatus for fractionating macro-molecules using asymmetric pulsed electrophoresis wherein an alternating electric field having two different orientations is applied, and one of the fields is stronger than the other in terms of duration or intensity, or the field is otherwise asymmetric.

The present invention relates to a method and apparatus for fractionation of charged macro-molecules such as DNA. DNA solution is loaded into a matrix including an array of obstacles. An alternating electric field having two different fields at different orientations is applied. The alternating electric field is asymmetric in that one field is stronger in duration or intensity than the other field, or is otherwise asymmetric. The DNA molecules are thereby fractionated according to size and are driven to a far side of the matrix where the fractionated DNA is recovered. The fractionating electric field can be used to load and recover the DNA to operate the process continuously.

## BRIEF DESCRIPTION OF THE DRAWINGS

Other important objects and features of the invention will be apparent from the following Detailed Description of the Invention taken in connection with the accompanying drawings in which:

**FIG. 1** shows conventional gel electrophoresis.

**FIG. 2** is a diagram showing asymmetric pulsed-field electrophoresis in micro/nano-fabricated matrices according to the present invention.

**FIG. 3** is a diagram showing the basic principle of asymmetrical pulsed electrophoresis of the present invention.

**FIG. 4** shows the way stretched DNA molecules move under asymmetrical pulsed electric field.

**FIG. 5** shows a support material (matrix) for use in fractionation of DNA according to the present invention.

**FIG. 6A** is a top view and **FIG. 6B** is a side view of the microfabricated support material shown in **FIG. 5**.

**FIG. 7** shows fractionation of T4 and T7 DNA.

## DETAILED DESCRIPTION OF THE INVENTION

The present invention relates to a method and apparatus for fractionation of charged macro-molecules such as DNA. DNA solution is loaded into a matrix including an array of obstacles. An alternating electric field having two different fields at different orientations is applied. The alternating electric field is asymmetric in that one field is stronger in duration or intensity than the other field, or is otherwise asymmetric. The DNA molecules are thereby fractionated according to size and are driven to a far side of the matrix where the fractionated DNA is recovered. The fractionating electric field can be used to load and recover the DNA to operate the process continuously.

The present invention provides a method and apparatus for the fractionation of macro-molecules on micro/nano-fabricated support materials (a.k.a. matrices). Because the motion of DNA molecules can be accurately controlled in micro/nano-fabricated environments, the fractionation of DNA can be achieved with very high resolution in a short time (i.e. seconds), even for DNA molecules larger than 100 kbp. In addition, the process can be operated continuously, i.e., DNA is loaded, fractionated, and recovered at the same time. Moreover, because this method exploits micro/nano-fabricated structure, it can be readily integrated into lab-on-a-chip devices as a component.

According to the present invention, DNA molecules enter from one point or loading channel 14 on the boundary 12 of the matrix 10 as shown in **FIG. 2**. The molecules are subsequently fractionated into different bands at different orientations, according to their sizes, as they are driven towards the other side 13 of the matrix 10, where the purified DNA molecules

30 are finally recovered. The DNA molecules are fractionated into short fragments 32 at one end, long fragments 36 at the other end, and medium fragments 34 therebetween. The electric field ( $E_1$  and  $E_2$ ) that fractionates the DNA sample can also be used to load and recover the sample, enabling the process to be operated continuously.

A mixture of DNA molecules emerges continuously from the loading channel. The support material comprises a micro/nano-fabricated porous structure, in which DNA molecules can move. An alternating electric field, shown in  $E_1$  and  $E_2$ , is applied across the whole matrix.  $E_1$  and  $E_2$  are at an angle with respect to each other, preferably an obtuse angle, and have different intensities and/or durations. Because DNA molecules are stretched and moving in a zigzag way under the alternating field, shorter fragments move at an angle to longer fragments.

When DNA molecules are subject to an alternating electric field between two orientations at an angle such as an obtuse angle, they are stretched to different lengths according to their molecular weight. Referring to **FIG. 3**, let the end-to-end length of a stretched DNA molecule be  $x$ . Assume that electric field  $E_1$  displaces every DNA molecules by approximately the same displacement  $\alpha e_1$ , whereas  $E_2$  displaces every DNA molecules by approximately  $\beta e_2$  ( $e_1$  and  $e_2$  are unit vectors, and both  $\alpha$  and  $\beta$  are positive numbers, since DNA molecules are negatively charged and move opposite to an applied electric field). This is a valid assumption because it is known that all DNA molecules have virtually the same mobility due to the fact that the long range hydrodynamic interaction is shielded by the counter ion layers. For the simplicity, let  $\alpha$  be larger than  $\beta$ . This can be achieved by pulsing along  $-e_1$  longer than along  $-e_2$ , and/or by making the electric field stronger along  $-e_1$  than along  $-e_2$ . Because the electric field is alternating

between two different directions, the DNA molecules will move in a zigzag way. Ideally, the electric field is chosen so that  $x < \beta < \alpha$ . The net motion of very short DNA molecules ( $x \ll \beta$ ) in one pulsing cycle (a cycle refers to applying  $E_1$ , then  $E_2$ ) is simply  $\alpha e_1 + \beta e_2$ . On the contrary, very long molecules ( $x > \beta$ ) travel  $(\alpha - \beta) e_1$  in a cycle. Even though this could be rather surprising at first glance, it is not hard to understand if it is realized that when the field is switched from one to the other, the tails of DNA strands become the ends that lead the motion and the heads follow, as shown in **FIG. 4**. In principle, we can predict the angles of the bands into which DNA mixtures are fractionated by this technique, if the stretched lengths of DNA molecules are smaller than or equal to  $\beta$ . Within this range ( $x < \beta$  or  $x = \beta$ ), the net motion of DNA molecules in one cycle is  $(\alpha - x) e_1 + (\beta - x) e_2$ . Purified DNA molecules can be recovered at the bottom of the support material, after many cycles. In one cycle, a DNA molecule stretched to length  $x$  will travel  $(\alpha - x) e_1 + (\beta - x) e_2$ .

As shown in **FIG. 4**, an alternating electric field not only stretches DNA molecules to a linear conformation, but also makes them to move in a zigzag way. The initial position of a DNA molecule is labeled as 0. The big dot on one end of the DNA represents the “head” of the molecule. The other end of the molecule is referred to as the “tail”. When  $E_1$  is applied, the DNA molecule moves to position 1. The tail leads the motion as the electric field is switched to  $E_2$ . By the end of one cycle, the molecule moves to position 2, and the net displacement in one cycle is  $(\alpha - x) e_1 + (\beta - x) e_2$ .

By electric field, what is meant is the spatial average of the field around a location over a length scale of several obstacles, not the microscopic field distribution around a single obstacle.

Any electric field at a given location, whose direction varies with time, can be resolved uniquely into two sequences of electric pulses according to the instantaneous direction of the field. The first sequence of electric pulses comprises the electric field pointing to one side of the average field vector over the whole period of time when the field is applied to fractionate the molecules. The second sequence of electric pulses comprises the electric field pointing to the other side of the average field vector. If the field vector at a moment is at the same direction or at the opposite direction of the average field vector, it is excluded in either of the pulse sequence. By asymmetrical electric field, what is meant is that the two sequences of electric pulses, resolved from a given electric field, as a function of time, have vector integrals over time that is not symmetric about the time-averaged field direction. Said another way, the electric fields, fields

$\vec{E}(t)$  whose odd-order integrals over time,  $\int |\vec{E}(t)|^n \vec{E}(t) dt$ , are not at the time-average field orientation for every  $n$ , where  $n$  is any positive even integer. As such, by applying electric fields with different orientations and different strengths, i.e. different durations or different intensities or both, one applies an asymmetric field. Asymmetric fields can also be generated by sweeping signals in terms of orientation, duration and intensity. In the past, the field has first and second pulse sequences whose vector integrals over time are symmetrical about the average field.



## Experimental Results

The following example uses a microfabricated matrix 10. As shown in **FIG. 5**, the matrix 10 consists of two parts: a microfabricated array of obstacles 20 in quartz, and a cap layer 18 that is hermetically bonded to the microfabricated side of the quartz substrate 16. The quartz substrate 16 is surface-micromachined using standard microfabrication techniques. The substrate is subsequently bonded to a glass cap layer 18 hermetically. The cavities between the substrate and the cap layer become microfluidic channels in which DNA molecules are fractionated. The dimensions of this microfabricated device are depicted in **FIGS. 6a** and **6b**. **FIG. 6a** is the top view of the matrix 10, and **FIG. 6b** is a side view of the matrix 10. The matrix 10 in this case is a hexagonal array of obstacles 20. Each obstacle 20 comprises a cylindrical post 2  $\mu\text{m}$  in diameter. The center-to-center distance between neighboring obstacles is 4  $\mu\text{m}$ . The uniformity of the electric field across the whole matrix is controlled accurately by the peripheral structures surrounding the matrix. **FIG. 7** shows the fractionation of T4 (169 kbp) and T7 (40 kbp) DNA molecules. The pulse condition is  $E_1 = 120 \text{ V/cm}$  at  $60^\circ$  with respect to the horizontal boundary, and  $E_2 = 60 \text{ V/cm}$  at  $-60^\circ$ . The DNA injected into the matrix is 10  $\mu\text{g/ml}$  of T4 DNA and 10  $\mu\text{g/ml}$  of T7 DNA in  $1/2$  TBE buffer. The duration of  $E_1$  is identical to that of  $E_2$ , which is 166 msec. The frequency at which the electric field alternates is 3 Hz. Clearly, the DNA mixture separates into two bands.

Having thus described the invention in detail, it is to be understood that the foregoing description is not intended to limit the spirit and scope thereof. What is desired to be protected by Letters Patent is set forth in the appended claims.